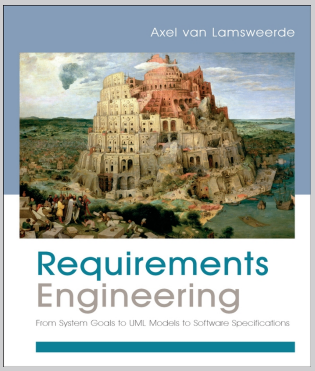
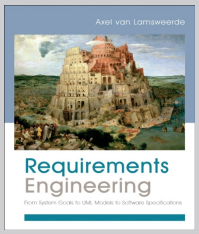
Requirements Engineering

From System Goals
to UML Models
to Software Specifications

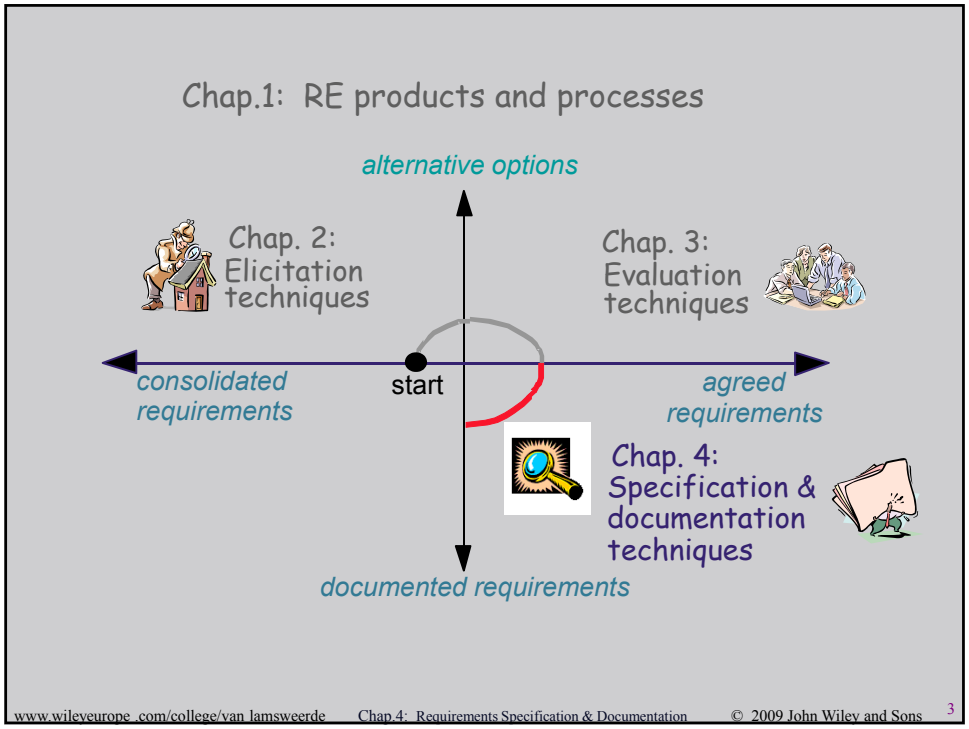


Axel Van Lamsweerde



Fundamentals of RE

Chapter 4
Requirements Specification & Documentation


Chap.1: RE products and processes
alternative options
Chap. 2: Elicitation techniques
Chap. 3: Evaluation techniques
consolidated requirements
start
agreed requirements
Chap. 4: Specification & documentation techniques
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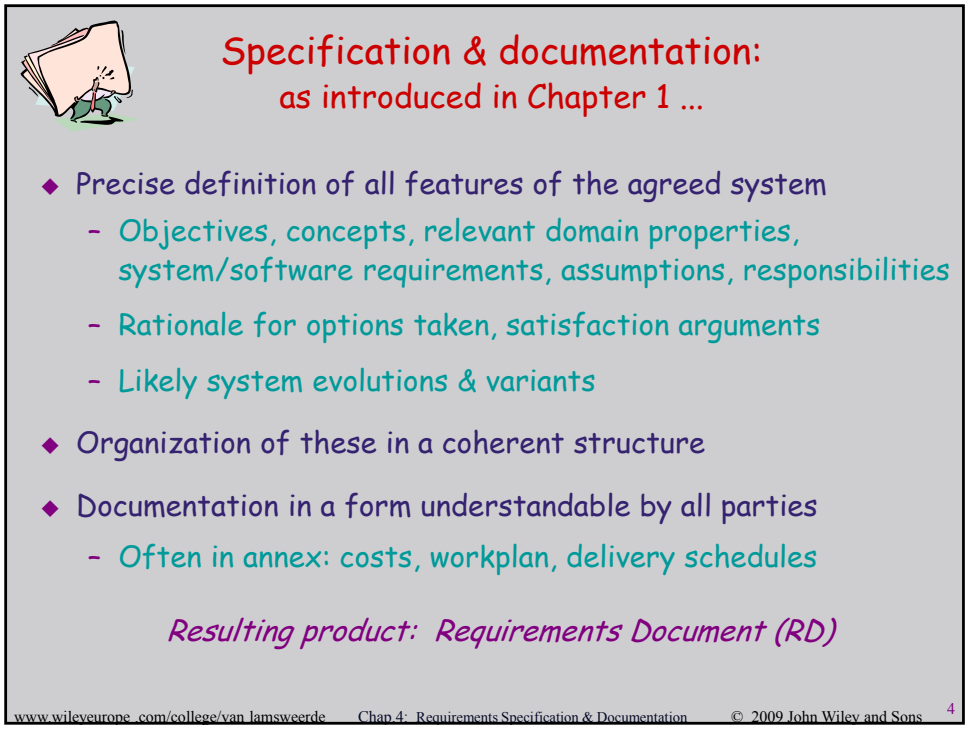
Specification & documentation:
as introduced in Chapter 1 ...
Precise definition of all features of the agreed system
Objectives, concepts, relevant domain properties, system/software requirements, assumptions, responsibilities
Rationale for options taken, satisfaction arguments
Likely system evolutions & variants
Organization of these in a coherent structure
Documentation in a form understandable by all parties
Often in annex: costs, workplan, delivery schedules
Resulting product: Requirements Document (RD)
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Requirements specification & documentation: outline

- Free documentation in unrestricted natural language
- Disciplined documentation in structured natural language
  - Local rules on writing statements
  - Global rules on organizing the Requirements Document
- Use of diagrammatic notations
  - System scope: context, problem, frame diagrams
  - Conceptual structures: entity-relationship diagrams
  - Activities and data: SADT diagrams
  - Information flows: dataflow diagrams
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  - Stimuli and responses: R-net diagrams
  - Integrating multiple system views, multi-view spec in UML

Requirements specification & documentation: outline (2)

- Formal specification
  - Logic as a basis for formalizing statements
  - History-based specification
  - State-based specification
  - Event-based specification
  - Algebraic specification

Free documentation in unrestricted natural language

- Unconstrained prose writing in natural language (NL) ...
  - ☺ Unlimited expressiveness, communicability, no training needed
  - ☹ Prone to many of the spec errors & flaws (cf. Chap.1)
- In particular, ambiguities are inherent to NL; can be harmful

  "Full braking shall be activated by any train that receives an outdated acceleration command or that enters a station block at speed higher than *X* m.p.h. and for which the preceding train is closer than *Y* yards."
- Frequent confusions among logical connectives in NL
  - e.g. case analysis:

If Case1 **then** <Statement1>
or **if** Case2 **then** <Statement2> (amounts to **true**!)
vs. **If** Case1 **then** <Statement1>
and **if** Case2 **then** <Statement2>

Disciplined documentation in structured NL: local rules on writing statements

- Use stylistic rules for good NL spec, e.g.
  - Identify who will read this; write accordingly
  - Say what you are going to do before doing it
  - Motivate first, summarize after
  - Make sure every concept is defined before use
  - Keep asking yourself: *"Is this comprehensible? Is this enough? Is this relevant?"*
  - Never more than one req, assumption, or dom prop in a single sentence. Keep sentences short.
  - Use *"shall"* for mandatory, *"should"* for desirable prescriptions
  - Avoid unnecessary jargon & acronyms
  - Use suggestive examples to clarify abstract statements
  - Supply diagrams for complex relationships among items

(More in the book)

Disciplined documentation in structured NL: local rules on writing statements (2)

- Use decision tables for complex combinations of conditions

input if-conditions — binary filling with truth values

Train receives outdated acceleration command	T	T	T	T	F	F	F	F
Train enters station block at speed ≥ *X* mph	T	T	F	F	T	T	F	F
Preceding train is closer than *Y* yards	T	F	T	F	T	F	T	F
Full braking activated	X		X		X			
Alarm generated to station computer	X	X	X	X				

output then-conditions — one case = AND-combination

- Systematic, simple, additional benefits ...
  - Completeness check: 2^N columns required for full table
  - Table reduction: drop impossible cases in view of dom props; merge 2 columns differing only by single "T", "F" => "-"
  - Test cases for free (cause-effect coverage)

Disciplined documentation in structured NL: local rules on writing statements (3)

- Use standardized statement templates

Identifier --suggestive; hierarchical if compound statement

Category --functional or quality req, assumption, domain property, definition, scenario example, ...

Specification --statement formulation according to stylistic rules

Fit criterion --for measurability (see next slide)

Source --for traceability to elicitation sources

Rationale --for better understanding & traceability

Interaction --contribution to, conflict with other statements

Priority level --for comparison & prioritization

Stability, Commonality levels --for change management

Fit criteria make statements measurable

- Complement statements by quantifying the extent to which they must be satisfied [Robertson, 1999]
- Especially important for measurability of NFRs

Spec: The scheduled meeting dates shall be convenient to participants
Fit criterion: *Scheduled dates should fit the diary constraints of at least 90% of invited participants in at least 80% of cases*

Spec: Info displays inside trains shall be informative & understandable
Fit criterion: *A survey after 3 months of use should reveal that at least 75% of travelers found in-train info displays helpful for finding their connection*

Disciplined documentation in structured NL: global rules on organizing the RD

- Grouping rules: Put in same section all items related to common factor ...
  - system objective
  - system component
  - task
  - conceptual object
  - software feature
  - ...
- Global templates for standardizing the RD structure
  - domain-specific, organization-specific, company-specific

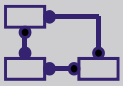
IEEE Std-830 template for organizing the RD

1. Introduction
    - 1.1 RD purpose
    - 1.2 Product scope — domain, scope, purpose of system-to-be
    - 1.3 Definitions, acronyms, abbreviations — glossary of terms
    - 1.4 References — elicitation sources
    - 1.5 Overview
2. General Description
    - 2.1 Product perspective — sw-environment boundary: interfaces with users, devices, other sw
    - 2.2 Product functions — functionalities of software-to-be
    - 2.3 User characteristics — assumptions about users
    - 2.4 General constraints — development constraints (hw limitations, implem platform, ...)
    - 2.5 Assumptions & Dependencies — environment assumptions (subject to change)
    - 2.6 Apportioning of requirements — optional, deferable reqs
3. Specific Requirements

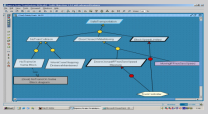
IEEE Std-830 template for organizing the RD (2)

3. Specific Requirements — *alternative templates for specific types of system*
    - 3.1 Functional requirements
    - 3.2 External interface reqs — NFRs: interoperability
    - 3.3 Performance reqs — NFRs: time/space performance
    - 3.4 Design constraints — NFRs: development reqs
    - 3.5 Software quality attributes — NFRs: quality reqs
    - 3.6 Other requirements — NFRs: security, reliability, maintainability
Appendices
Index

- Variant: VOLERE template [Robertson, 1999]
    - explicit sections for domain properties, costs, risks, development workplan, ...



Use of diagrammatic notations



- To complement or replace NL prose
- Dedicated to specific aspects of the system (as-is or to-be)
- Graphical: to ease communication, provide overview
- Semi-formal ...
  - Declaration of items in formal language (syntax, semantics)
    => surface checks on RD items, machine-processable
  - Informal spec of item properties in NL
- This chapter: typical sample of frequently used diagrams, showing complementarities
- Part 2: in-depth study + systematic method for building complex models using integrated set of diagrams

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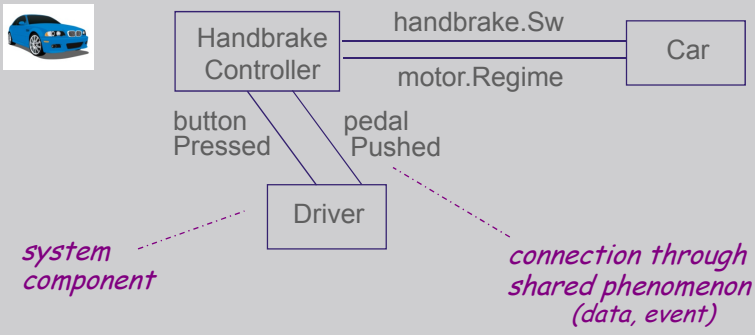
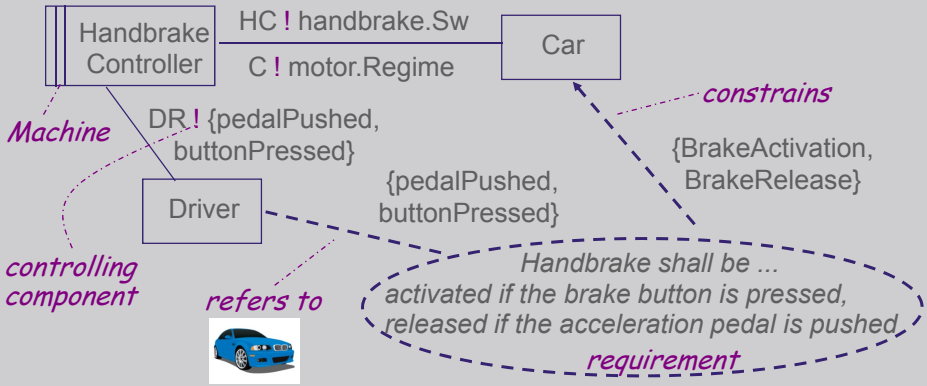
System scope: context diagrams

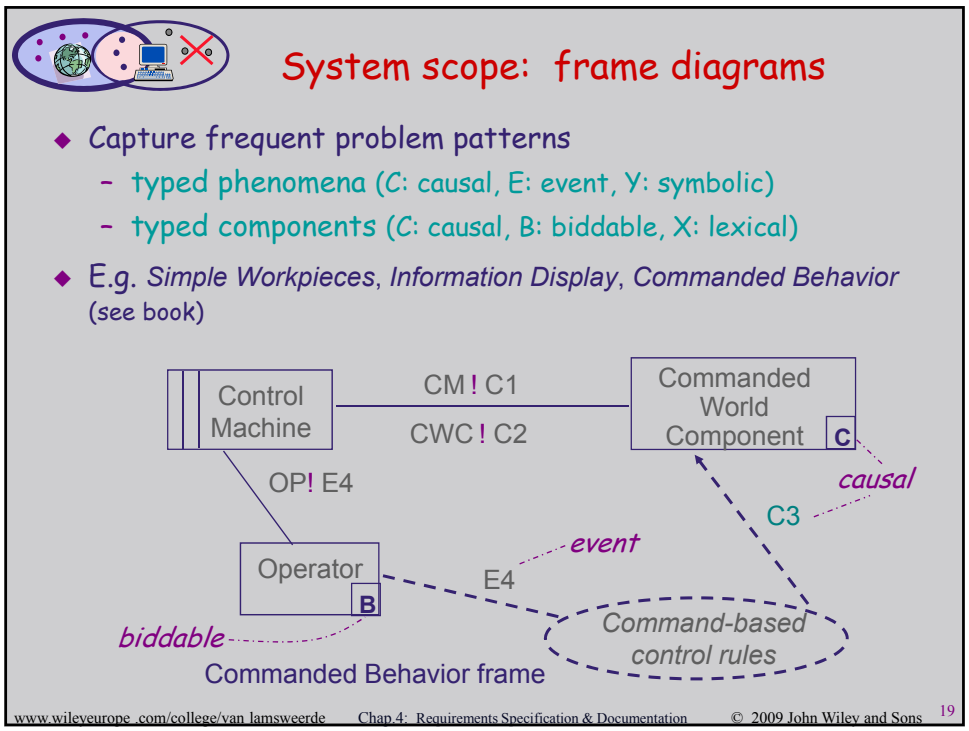
- Declare system components & their interfaces [DeMarco '78]
  - => system structure
    - what is in system, what is not
    - environment of each component: neighbors, interfaces



System scope: problem diagrams

- More detailed form of context diagram: highlights...
  - the Machine among system components
  - for shared phenomenon: who controls it, who monitors it
  - requirements, components affected by them




System scope: frame diagrams
Capture frequent problem patterns
typed phenomena (C: causal, E: event, Y: symbolic)
typed components (C: causal, B: biddable, X: lexical)
E.g. Simple Workpieces, Information Display, Commanded Behavior (see book)
Control Machine
CM ! C1
CWC ! C2
Commanded World Component
C
causal
C3
OP! E4
event
Operator
B
E4
biddable
Command-based control rules
Commanded Behavior frame
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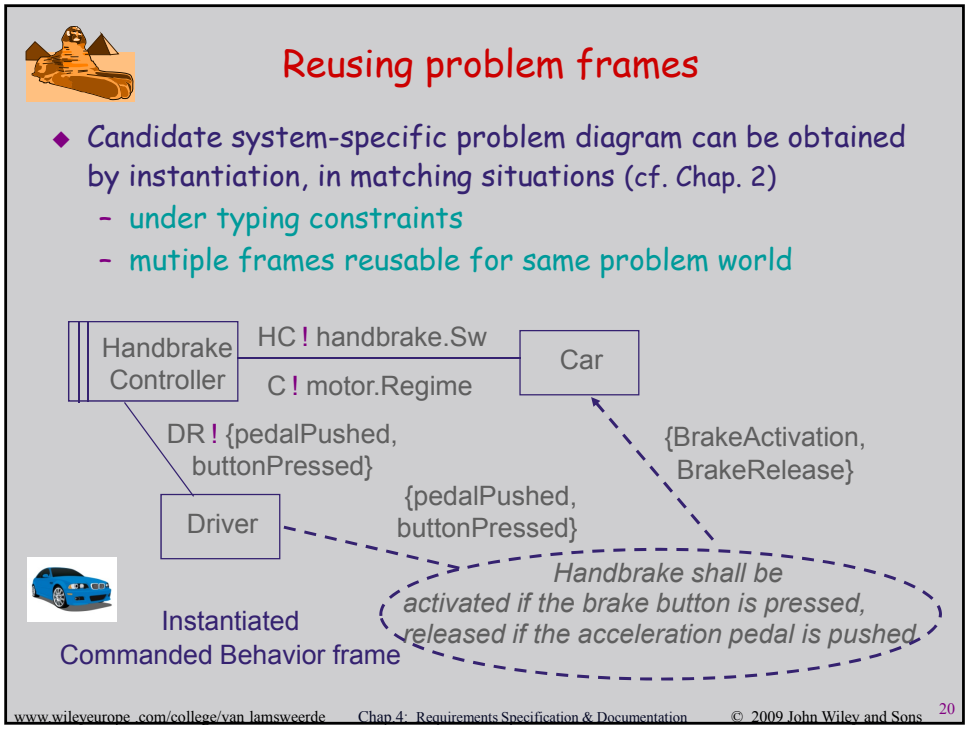
Reusing problem frames
Candidate system-specific problem diagram can be obtained by instantiation, in matching situations (cf. Chap. 2)
under typing constraints
mutiple frames reusable for same problem world
Handbrake Controller
HC ! handbrake.Sw
C ! motor.Regime
Car
DR ! {pedalPushed, buttonPressed}
{BrakeActivation, BrakeRelease}
Driver
{pedalPushed, buttonPressed}
Handbrake shall be activated if the brake button is pressed, released if the acceleration pedal is pushed
Instantiated Commanded Behavior frame
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Conceptual structures: entity-relationship diagrams

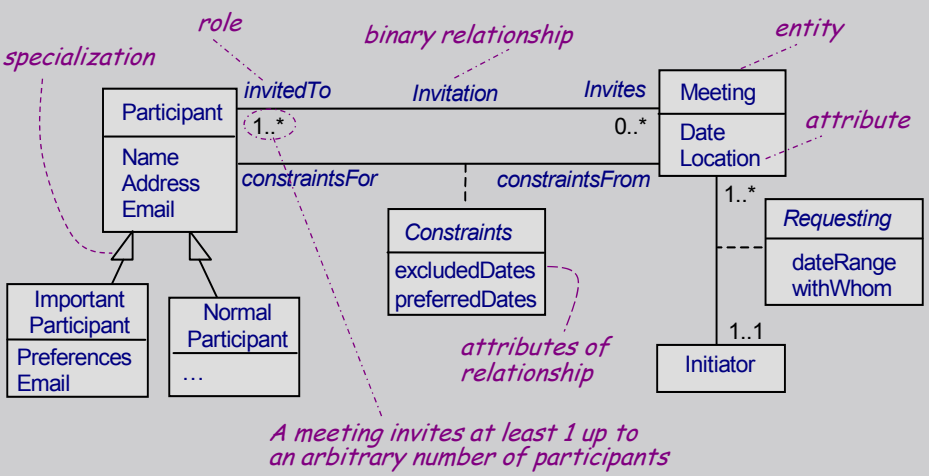
- Declare conceptual items, structure them
- Entity: class of concept instances ...
  - having distinct identities
  - sharing common features (attributes, relationships)

  e.g. Meeting, Participant
- N-ary relationship: feature conceptually linking *N* entities, each playing a distinctive role ($N \geq 2$)
  - Multiplicity, one one side: min & max number of entity instances, on this side, linkable at same time to single tuple of entity instances on the other sides

  e.g. Invitation linking Participant and Meeting
- Attribute: feature intrinsic to an entity or a relationship
  - has range of values

  e.g. Date of Meeting

Entity-relationship diagram: example



Multiplicities may capture *requirements* or *domain properties*

☹ No distinction between prescriptive & descriptive

Entity-relationship diagrams (2)

- Entity specialization: subclass of concept instances, further characterized by specific features (attributes, relationships)
  - by default, inherits attributes & relationships from superclass
  - rich structuring mechanism for factoring out structural commonalities in superclasses

  e.g. ImportantParticipant, with specific attribute Preferences
  Inherits relationships Invitation, Constraints, attribute Address
  (Email of ImportantParticipant *inhibits* default inheritance)
- Diagram annotations: to define elements precisely
  - essential for avoiding spec errors & flaws

  e.g. annotation for Participant:

  "Person expected to attend the meeting, at least partially, under some specific role. Appears in the system when the meeting is initiated and disappears when the meeting is no longer relevant to the system"

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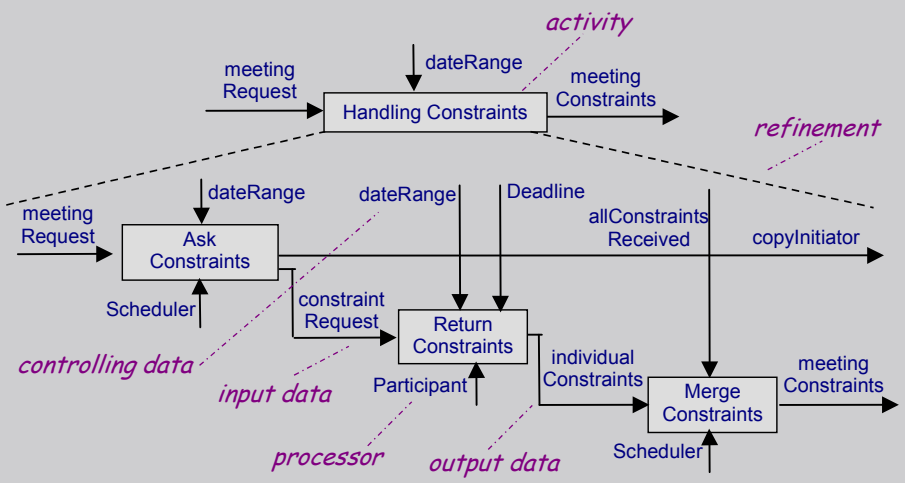
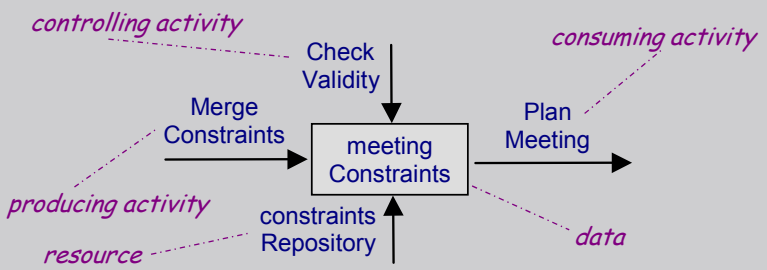
Activities and data: SADT diagrams

- Capture activities & data in the system (as-is or to-be)
- Actigram: relates activities through *data* dependency links
  - East → : input data; West → : output data
  - North → : controlling data/event; South → : processor
  - Activities refinable into sub-activities
- Datagram: relates data through *control* dependency links
  - East → : producing activity; West → : consuming activity
  - North → : validation activity; South → : needed resources
  - Data refinable into sub-data
- Data-activity duality:
  - data in actigram must appear in datagram
  - activities in datagram must appear in actigram

SADT diagrams: actigram example



SADT diagrams: datagram example

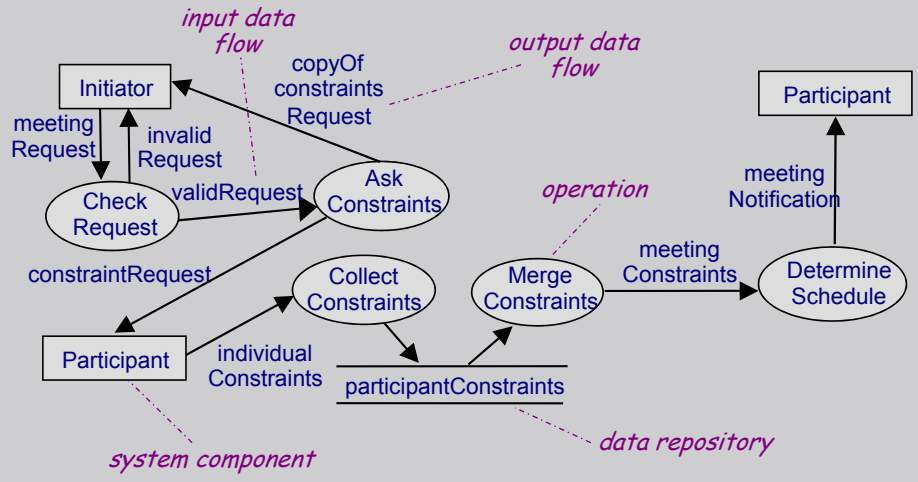


- Consistency/completeness rules checkable by tools
  - Every activity must have an input and an output
  - All data must have a producer and a consumer
  - I/O data of an activity must appear as I/O data of subactivities
  - Every activity in a datagram must be defined in an actigram, ...

Information flows: dataflow diagrams

- Capture system operations linked by data dependencies
  - simpler but less expressive than actigrams
- Operation = data transformation activity
- Input, output links = data flows
  - operation needs data flowing *in* to produce data flowing *out* (≠ control flow !)
- Data transformation rule to be specified ...
  - in annotation (structured NL)
  - or in another DFD (operation refinement, cf. SADT)
- System components, data repositories = origins, ends of flow
- Consistency/completeness rules checkable by tools, cf. SADT

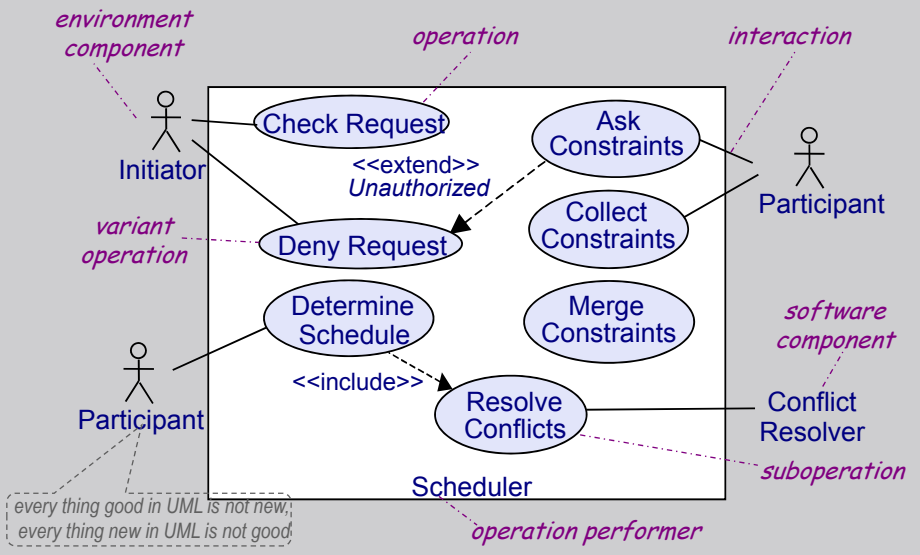
Dataflow diagram: example



System operations: use case diagrams

- Capture operations to be performed by a system component & interactions with other components
  - yet simpler, outline view ... but vague
  - to be made precise by annotations, interaction scenarios, ...
  - introduced in UML to replace DFDs
- Structuring mechanisms ...
  - <<include>>: to specify "suboperation"
  - <<extend>> + precondition: to specify "variant" operation in exception case

Use case diagram: example



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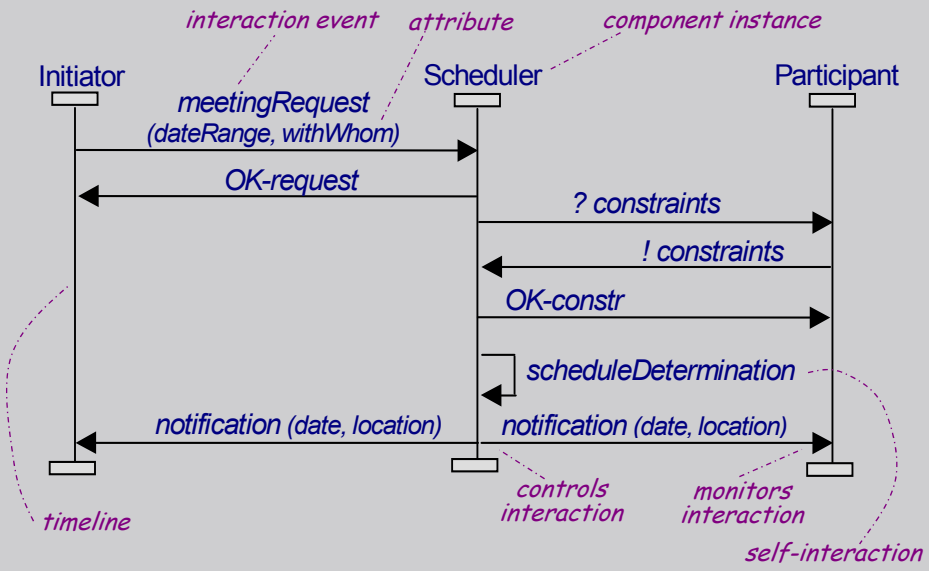
Interaction scenarios: event trace diagrams

- Capture positive scenarios by sequences of interactions among instances of system components (cf. Chap. 2)
  - variants: MSC (ITU), sequence diagrams (UML, cf. Chap. 13)
- Parallel composition of timelines
  - one per component instance
- Pairwise directed interactions down timelines
  - information transmission through event attributes
- Interaction event synchronously controlled by source instance & monitored by target instance
  - total order on events along timeline (event precedence)
  - partial order on all diagram events

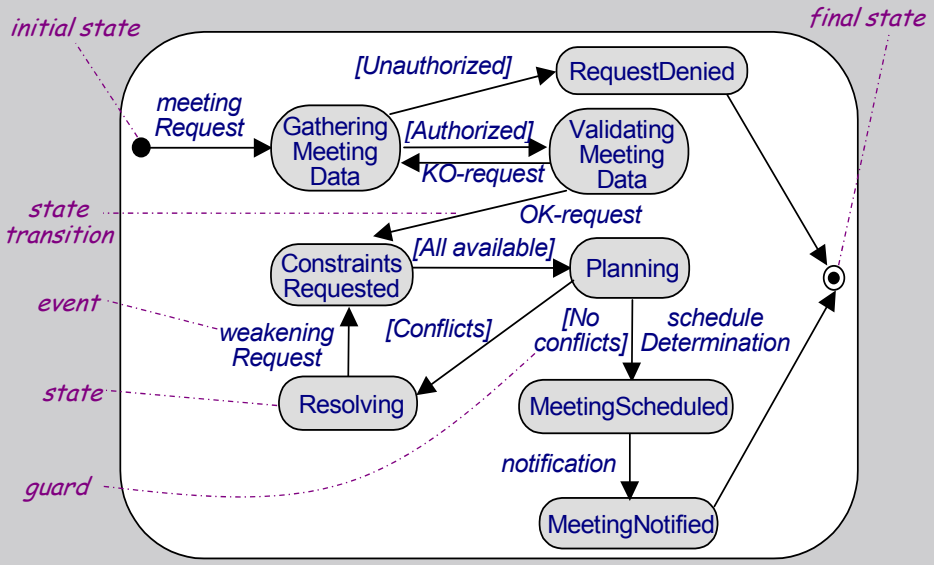
Event trace diagram: example

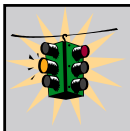


System behaviors: state machine diagrams

- Capture the admissible behaviors of system components
- Behavior of component instance = sequence of state transitions for the items it controls
- SM state = set of situations where a variable characterizing a controlled item has always the same value
  - e.g. state MeetingScheduled: always same value for Date, Location (while other variable WithWhom on Meeting may change value)
  - Initial, final states = states where item appears, disappears
  - States may have some duration
- SM state transition: caused by associated event
  - if item in *source* state and event *ev* occurs then it gets to *target* state
  - Events are instantaneous phenomena

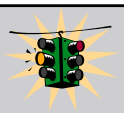
Example of state machine diagram: meeting controlled by a meeting scheduler





State machine diagrams: transitions and guards

- Event occurrence is a *sufficient* condition for transition firing
  - Event can be external stimulus (e.g. meetingRequest) or application of internal operation (e.g. determineSchedule)
- Guard = *necessary* condition for transition firing
  - Item gets to *target* state ...
    if item is in *source* state and event *ev* occurs
    and only if *guard* condition is true
  - Guarded transition with no event label:
    fires as soon as *guard* gets true (= trigger condition)
- Non-deterministic behavior: multiple outgoing transitions with same event and no or overlapping guards
  - often to be avoided for safety, security reasons

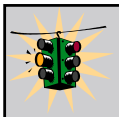



Scenarios and state machines

- SM trace = sequence of successive SM states up to some point
  - e.g. ‹ GatheringMeetingData, RequestDenied ›
  - always finite, but SM diagram may have infinitely many traces
- A SM diagram generalizes ET diagram scenarios:
  - from specific instances to *any* component instance
  - *trace coverage:* SM traces include ET traces, and (many) more

    e.g. scenario/SM trace from previous slides:

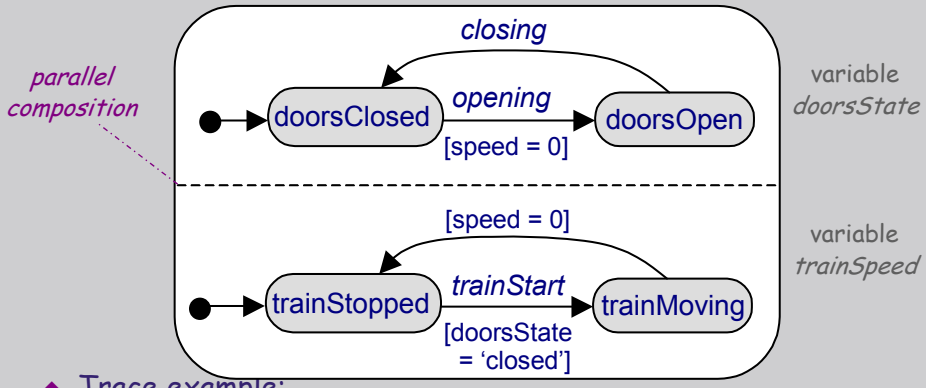
    ‹ ValidatingMeetingData; ConstraintsRequested; Planning; MeetingScheduled; MeetingNotified ›



Concurrent behaviors and statecharts

- Components often control *multiple* items in parallel
- Problems with flat SM diagram ...
  - *N* item variables each with *M* values => M^N states !
  - same SM state mixing up different variables
- Statechart = parallel composition of SM diagrams [Harel, 1987]
  - one per variable evolving in parallel
  - statechart state = aggregation of concurrent substates
  - from M^N explicit SM states to $M \times N$ statechart states !
- Statechart trace = sequence of successive aggregated SM states up to some point
- Interleaving semantics: for 2 transitions firing in same state, one is taken after the other (non-deterministic choice)

Statechart example

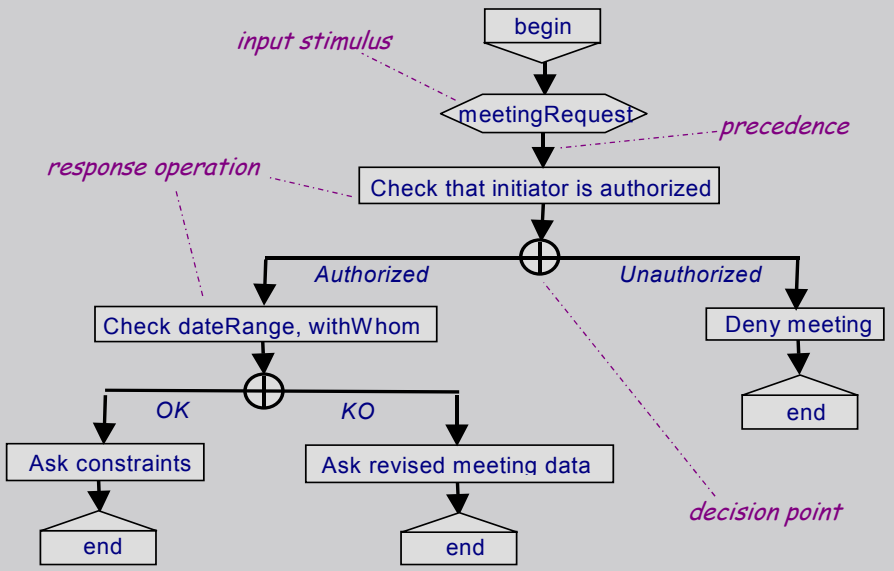


- Trace example:
  < (doorsClosed, trainStopped); (doorsClosed, trainMoving); (doorsClosed, trainStopped); (doorsOpen, trainStopped) >
- Model-checking tools can generate counterexample traces leading to violation of desired property (cf. chap. 5)

Stimuli and responses: R-net diagrams

- Capture all required responses to single stimulus [Alford, 1977]
  - chain of response operations to be performed by a system component
  - operation may generate stimuli for other R-nets
- Decision points, operation application under conditions
- Good for visualizing ...
  - answers to *WHAT IF?* questions
  - required software reactions to environment events

R-net diagram: example



Integrating multiple system views

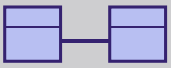
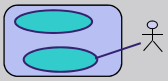
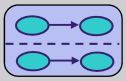
- Diagrams of different types cover different, complementary views of the system (as-is or to-be)
  - components & interfaces, conceptual structures, operations, flows, interaction scenarios, behaviors, ...
- Overlapping aspects => integration mechanism needed for ensuring compatibility & complementarity among diagrams
- Standard mechanism: inter-view consistency rules the specifier should meet
  - cf. static semantics rules enforced by compilers
    "every used variable must be declared"
    "every declared variable must be used", ...
  - can be used for inspection checklists
  - enforceable by tools
  - constrain diagram evolution

Inter-view consistency rules: examples

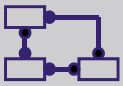
- Every component & interconnection in a problem diagram must be further specified in an ET diagram
- Every shared phenomenon in a problem diagram must appear as event in an ET diagram or as entity, attribute, or relationship in an ER diagram
- Every data in a flow or repository of a DFD diagram must be declared as entity, attribute, or relationship in an ER diagram
- Every state in a SM diagram must correspond to some value for some attribute or relationship in an ER diagram
- Every interaction event in an ET scenario must appear in a corresponding SM diagram

Multi-view specification in UML

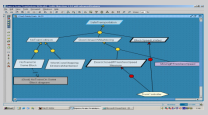
The Unified Modeling Language (UML) has standardized notations for diagrams relevant to RE

- Class diagrams: ER diagrams for structural view 
- Use case diagrams: outline of operational view 
- Sequence diagrams: ET diagrams for scenarios 
- State diagrams: SM diagrams for behavioral view 

Further studied in Chaps. 10-13 in a systematic method for building multi-view models



Diagrammatic notations: pros & cons



- Formal declaration of different system facets
  + informal annotations of properties for higher precision
- Graphical declaration =>
  - ☺ overview & structuring of important aspects
  - ☺ easy to understand, communicate
  - ☺ surface-level analysis, supported by tools (e.g. query engines)
- Semi-formal specification =>
  - ☹ language semantics may be vague (different interpretations)
  - ☹ only surface-level aspects formalized, not item properties
  - ☹ limited forms of analysis
  - ☹ functional and structural aspects only

=> *formal specification needed for mission-critical aspects*

Requirements specification & documentation (1) : summary

- Free documentation in unrestricted NL is subject to errors & flaws
- Disciplined documentation in structured NL is always necessary
  - Local rules on statements: stylistic rules, decision tables, statement templates
  - Global rules on RD organization: grouping rules, structure templates
- Diagrams for graphical, semi-formal spec of complementary aspects
  - System scope: context, problem, frame diagrams
  - Conceptual structures: entity-relationship diagrams
  - Activities and data: SADT diagrams
  - Information flows: dataflow diagrams
  - System operations: use case diagrams
  - Interaction scenarios: event trace diagrams
  - System behaviors: state machine diagrams
  - Stimuli and responses: R-net diagrams
  - Integrating multiple views, multi-view spec in UML

Requirements specification & documentation (2) : formal specification

- Logic as a basis for formalizing statements
- History-based specification
- State-based specification
- Event-based specification
- Algebraic specification